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# THE REQUISITE AND QUALIFYING CONDITIONS

# OF

# ARTESIAN WELLS

BY

## THOMAS C. CHAMBERLIN

[EXTRACT FROM THE FIFTH ANNUAL REPORT OF THE DIRECTOR, 1883-'84.]

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OF

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BY

THOMAS C. CHAMBERLIN.

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ARTESIAN WELL AT PRAIRIE DU CHIEN, WISCONSIN.

# REQUISITE AND QUALIFYING CONDITIONS OF ARTESIAN WELLS.[1]

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BY T. C. CHAMBERLIN.

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## INTRODUCTION.

The basal principles of artesian wells are simple. The school-boy reckons himself their master. But the real problems they present are complex. It is a combination of varying conditions, rather than the application of simple principles, that determines success or failure. A clear statement of these conditions is as rare as a simple, but incomplete, exposition is familiar. This is perhaps not so much due to any special intricacy of the problem, or to any grave obstacle to a clear statement, as to the simple fact that it has been neglected.

It has not been the leading subject of any profession. Few drillers make the causes and conditions of artesian flow a special study, or find it within their province to master the geological elements of the question. Few geologists, among the multitude of more obtrusive resources pressed upon their attention, find themselves able to pursue the subject into its practical details. Few citizens have occasion more than once or twice in their lives to give the matter special consideration. This, however, is growing steadily less and less true. Drillers are developing the sinking of artesian wells into a specialty, and, through the aid of geological reports, are mastering the stratigraphical elements of the problem in their several regions. Geologists are solicited with increased frequency for advice and prognostic opinions. Citizens are becoming more widely interested in both the practical and the theoretical aspects of the subject.

Its importance does not need argument, though it may need emphasis. The problem of a pure and adequate water supply is among the gravest questions that now lay under tribute the thoughts of sanitarians. Artesian wells form one, but only one, source of such a supply; sometimes as inadequate or impracticable as, at others, generous and beneficent. Were they an unfailing source, a universal possibility, so great a resource would command its own full measure of attention. Were they always inadequate, or unsatisfactory, they might be easily dismissed. This inconstant feature is an element that makes need for a discriminative discussion of the conditions that determine success or failure, since they are a valuable resource in certain regions and under certain limitations, while, in other regions and beyond assignable limits, they are only a lure to useless expenditure. On the one hand, large sums are needlessly spent in endeavors to obtain these fountains, where the essential conditions are altogether wanting, and, on the other, large possibilities of good have lain neglected, to the great sanitary and industrial loss of citizens.

---

[1] The term artesian wells in this discussion is applied only to those that flow at the surface. Unfortunately the term is frequently used to denote deep wells that do not flow, a use that is to be condemned.

It is the aim of this article to gather into a simple and convenient form such information relative to the necessary and qualifying conditions of artesian wells as may be capable of brief, general statement, and may seem to be serviceable alike to citizen, driller, and geologist. There will be no attempt, however, to make it an exhaustive exposition of the subject from the individual stand-point of either. The citizen will desire specific information concerning cost, quality of water, etc., that cannot be answered in a general discussion. The driller will desire constructive details and local particulars relating to the succession of beds, the texture and structure of the rock, etc., that only exhaustive geological descriptions, specially interpreted for his purpose, can supply. The geologist will desire a fuller discussion of the elements that enter into the formation of a professional opinion. It is obvious that, so far as these are dependent on local and varying conditions, satisfactory general answers are impracticable, and, in so far as they are specifically technical, they are here inappropriate. It is the ground of common interest, lying in the conditions of success, that I aim to cover. In addition to all that can be said here, special problems will need special study.

If there lingers in the mind any sense of marvel at the flow of artesian wells, it is best to cast it away at the outset. Artesian flow is but an expression of the common law of flowage, made a little unusual, it is true, by its special conditions. Any seeming strangeness springs from our partial observation. We see but a part of the stream. The rest lies hidden in the earth's depths, a realm which the imagination is prone to people with mysteries. Moreover, the part we do most see is a *rising* stream, that comes gushing up in the face of the dogma that water "never runs up hill." But water flowing up hill is one of the commonest facts of nature, an every day, an everywhere occurrence, illustrated in every brook, rill, and river, not to say spring. Stir up a little trash in the bottom of any deep pool in a brook, and see how readily it is borne up the slope of the pool-bed, and out over the shallows below. Disturb the bottom mud above a dam, and watch it ascend the steep slope, and pass over the weir.

Certain portions of the water of every stream are always "running up hill," though its average mass is moving down.

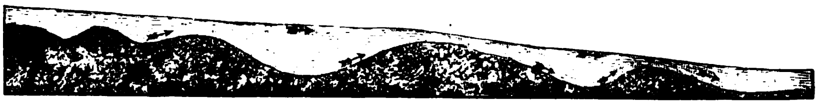

FIG. 7.—Longitudinal section of a stream, illustrating, in part, its upward currents, subordinate to the general downward flowage.

The bottom layer flows up and down according to the inequalities of the bed, while the top layer declines more uniformly with the surface slope.[2] In proportion as the stream is rapid and crooked, these layers exchange places, and there is a tortuous upward and downward flow, in addition to that directly enforced by the bottom inequalities, though all are largely due to these. The flowing up is merely a way of flowing down, *i. e.*, the rising of a part permits the descent of a greater portion, or the greater descent of an equal or less part. No portion would rise, if it were not forced up by a superior portion pressing down. In the artesian stream, we only see the rising column issuing from the earth, and the brooklet that flows away. The more potent descending volume that forces the flow is concealed. This it is the mind's task to picture clearly.

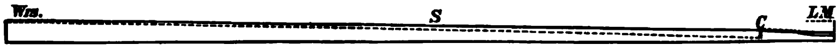

FIG. 8.—Section of the Chicago artesian stream, drawn to a nearly true scale. The dotted line represents the course of flow, exhibiting the long declining stream from the fountain-head in south-central Wisconsin, the short and *relatively* trivial rise in the wells at Chicago (C of the diagram), and the surface flow from these. The full line, G, representing the surface, shows the general decline of the stream. For the purpose of giving clear and striking illustrations, most diagrams of artesian wells are given enormously exaggerated vertical scales, and most of those of this paper are quite disproportionate in that respect, though the exaggeration has been greatly reduced. This diagram is introduced at the outset to forestall the erroneous impressions conveyed by such illustrations.

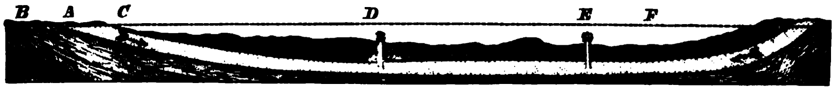

FIG. 9.—Ideal section illustrating the chief requisite conditions of artesian wells. A, a porous stratum; B and C, impervious beds below and above A, acting as confining strata; F, the height of the water-level in the porous bed A, or, in other words, the height of the reservoir or fountain-head; D and E flowing wells springing from the porous water-filled bed A.

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[2] It is not a little surprising to note how frequently this simple fact, common to all streams, is neglected in the study of glacial flows. The traces of extinct glacial currents are those formed by the bottom of the stream, whose ascending and descending courses are no stranger than those of the brook. We study one from the top and neglect the bottom, the other from the bottom and forget the top.

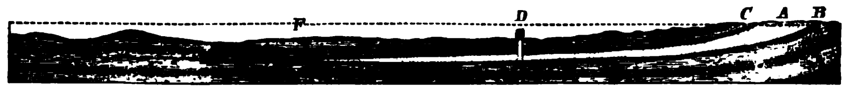

FIG. 10.—Section illustrating the thinning out of a porous water-bearing bed, A, inclosed between impervious beds, B and C, thus furnishing the necessary conditions for an artesian fountain, D.

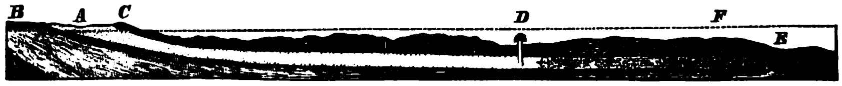

FIG. 11.—Section illustrating the transition of a porous water-bearing bed, A, into a close-textured impervious one. Being inclosed between the impervious beds B and C, it furnishes the conditions for an artesian fountain. D.

## ESSENTIAL FEATURES OF ARTESIAN WELLS.

The artesian stream has its source, its underground water-way, its ascent through the well, and its final descent in the rill that runs away. It is peculiar mainly in its underground conditions. Upon these, chiefly, the ascending flow depends.

*Typical examples.*—To fashion a simple idea of the common class of flowing wells, picture to the mind a pervious stratum through which water can readily pass. Below this let there be a water-tight bed, and let a similar one lie upon it, so that it is securely embraced between impervious layers. Suppose the edges of these layers to come to the surface in some elevated region (save that they may be covered with soil and loose surface material), while in the opposite direction they pitch down to considerable depths, and either come up again to the surface at some distance, thus forming a basin (Fig. 9), or else terminate in such a way (Fig. 10) or take on such a nature (Fig. 11) that water cannot escape in that direction. Now, let rain-fall and surface-waters penetrate the elevated edge of the porous bed, and fill it to the brim. That such beds are so filled is shown by ordinary wells, which commonly find a constant supply in them at no great depth. Now it is manifest that if such a water-fat bed be tapped by a boring at some point lower than its outcrop, the water will rise and flow at the surface because of the higher head in the upper edge of the bed. If the surface-water continually supplies the upper edge as fast as the water is drawn off below, the flow will be constant.

*Prerequisites.*—The leading conditions upon which artesian flows depend are involved in this simple conception. Drawn out they are as follows:

I. A pervious stratum to permit the entrance and the passage of the water.

II. A water-tight bed below to prevent the escape of the water downward.

III. A like impervious bed above to prevent escape upward, for the water, being under pressure from the fountain-head, would otherwise find relief in that direction.

IV. An inclination of these beds, so that the edge at which the waters enter will be higher than the surface at the well.

V. A suitable exposure of the edge of the porous stratum, so that it may take in a sufficient supply of water.

VI. An adequate rain-fall to furnish this supply.

VII. An absence of any escape for the water at a lower level than the surface at the well.

These may be considered in detail, and then attention directed to some special practical questions.

## THE WATER-BEARING BEDS.

There are two general methods by which water finds its way through the strata; in the one—the rock being close-textured—the water passes through fissures formed by fracture, or tubular channels formed by solution; in the other—the rock being open-textured—the water seeps through the pores, permeating the whole bed.[3]

1. *Fissured and channeled beds.*—Beds that offer only crevices and channels as water-ways are a very uncertain source of fountains, for open, continuous avenues of this class do not seem to be abundant in strata deeply buried, and the position of such as exist cannot be determined beforehand, so that there is no certainty of striking them.

The close-textured rocks that fall under attention here are chiefly the crystalline class (the granites, greenstones, etc.) and the limestones. The clay rocks (shales, etc.) are too compact to be in any available degree water-bearing; indeed, they form the chief confining strata.

The crystalline rocks are much fissured at the surface, and shrinkage has opened gaping crevices in them; but these avenues largely close up and disappear at moderate depths, and there are no sufficient grounds for supposing that they often afford facilities for a continuous, generous flow, where they have always lain under the protecting mantle of impervious strata, and have suffered the pressure of their weight. Experience confirms this. None of the igneous or metamorphic rocks are to be accounted available water-bearing strata unless some known local condition gives them exceptional possibilities.

The limestones are likewise much traversed by crevices near the surface, and are, besides, subject to the solvent action of the waters passing through them. These often form extensive underground channels, mammoth examples of which are found in the great elongated caves of

---

[3] Of course we are here considering only such generous supplies as are available for artesian purposes, not that slower penetration of rocks by water that is almost or quite universal.

Indiana and Kentucky. But, like the above, these prevail mainly in the superficial portion of the beds, and are chiefly confined to regions where the limestone stratum is not overlain by other rocks, and hence not available as a source of fountains. The reason of this is manifest, when it is considered that the solvent action is mainly accomplished by surface waters. These exhaust their solvent power before penetrating far. When the limestone is overlain by impervious beds, these surface waters are cut off, and hence solvent action is limited to such waters as entered at the distant outcropping edge. The cracks and cavities of deep-seated limestones are often found to be healed up with calcite, an index that the waters there are depositing, rather than solvent.

The grounds, therefore, for anticipating success in penetrating limestone for fountains, are not very flattering, though less adverse than in the crystalline rocks. However, limestones that have once been exposed to surface action, and thereby fissured and channeled, and subsequently buried beneath a thick mantle of drift clay, are not altogether unpromising. Not a few important flowing wells have been derived from them. But when the beds have always lain deeply buried beneath impervious strata, they have rarely been found productive, so far as my knowledge extends.

A little computation will show that even if such compact rocks were notably fissured and channeled, they would be a very questionable resource in deep, expensive wells. Suppose that vertical fissures or tubular channels traversed a given stratum at intervals of only 10 feet. It would be possible to sink twenty average bores between each two of them. If the fissures averaged as much as 6 inches, the chances of success would be about one in twenty, or only 5 per cent. of the whole, or, with a similar system of cross fissures, 10 per cent. If the case were really of this sort, however, connection with the channels might be made by firing torpedoes within the bore. But in fact deeply-buried limestones are to be esteemed a very uncertain dependence, while metamorphic and igneous rocks had better not be reckoned a dependence at all. Limestones that have been once at the surface, but afterward buried, may be locally serviceable.

2. *Porous beds.*—Quite in contrast with the close-textured beds, that are water-carriers only by virtue of fissures and channels, are the open-textured strata that constitute continuous water-filled sheets underspreading wide areas, and which can therefore almost certainly be tapped at the proper depth. Speaking in general terms, these are the only reliable sources of artesian wells.

To this class belong beds of sand, gravel, sandstone, conglomerate, and other less common rocks of loose granular texture. Some of the more porous chalks and granular limestones may be classed here. The common feature of the class lies in the construction of the rock from separate particles, loosely put together, leaving small open spaces between them. The porosity is of an interstitial, not vesicular, kind. A bed of sand is a typical illustration, and it will not be wide of the truth to speak of the whole class as sandstones. All sandstones, however, are not sufficiently porous to furnish a ready passage for water. In some the interspaces are filled with clayey or other impervious matter, that insinuated itself among the particles as they were being deposited originally; in others the pores were subsequently choked by deposits from solution and by compacting under pressure.

The degree of porosity is a very important consideration, when the volume of the flow is to be considered. If the entire rock is made up of sand-like particles the larger these are, in general, the greater the water-conveying capacity. Some sandstones are so fine-grained as to be almost impervious. The water merely oozes through them, and they are quite incapable of furnishing a generous flow. Others are so open-spaced that floods flow freely through them. In nature there is every gradation, from open gravels to close sandstones.

Besides, there is almost every possible intermixture of coarse and fine material. The constituents were not perfectly assorted. Fine sand and silt are interspersed among coarser grains, pebbles, and bowlders. This may reach almost any degree of influence upon the water-carrying capacity of the rock from a slight reduction to its almost complete extinction.

There is also a very wide range in the degree of consolidation after deposition. There are drift sands and gravels that are entirely loose and uncompacted, while, at the other extreme, are perfectly consolidated quartzites and analogous rocks. It is a general but quite unreliable rule that consolidation varies with the age of the formation, the Quaternary sands being looser than the Tertiary, the Tertiary looser than the Secondary, and so on. The rule is founded on reason; but there are many notable exceptions, as the Potsdam sandstone of the Upper Mississippi Valley, among the most ancient of the old life series, and yet among the most loose-textured, as well as the most generous of water-bearers. It is manifest, therefore, that we cannot rest with simple rules or general descriptions. The capabilities of each formation must be ascertained by direct observation of its constitution. This indicates one of the good offices subserved by critical descriptions of the texture of rocks, even of those which are coarsest and whose origin is most obvious. It is a suggestion that examinations be made more critical.

## THE CONFINING BEDS.

No stratum is entirely impervious. It is scarcely too strong to assert that no rock is absolutely impenetrable to water. Minute pores are well nigh all-pervading. To these are added microscopic seams, and to these again larger cracks and crevices. Consolidated strata are almost universally fissured. Even clay beds are not entirely free from partings.

But in the study of artesian wells we are not dealing with absolutes but with availables. A stratum that successfully restrains the most of the water, and thus aids in yielding a flow, is serviceably impervious. It may be penetrated by considerable quantities of water, so that the leakage is quite appreciable and yet be an available confining stratum. The nearest approach to an entirely impervious bed is furnished by a thick layer of fine, unhardened clay. In this case solidifying permits the formation of fissures and the clay rocks are less impervious than the original clay beds. The clayey shales rank next as confining strata, after which follow in uncertain order shaly limestones, shaly sandstones, the various crystalline rocks, and even compact sandstones. Paradoxical as it may seem water itself may form a confining agent. I shall presently attempt to show that it is even an agency of considerable importance. In a different and more forced sense an illustration may be found in the pool of the brook before cited. The water flows from the bottom of the pool up the slope and out, because it is pressed by the water behind and *confined* by that above. Each upper layer is a confining stratum to each lower one. This, however, is not the sense in which it is a recognizable agency in artesian flows.

1. *The confining stratum below.*—It is our habit to be less solicitous about the tightness of the cover of a water-bearing vessel than of its bottom. The reverse is the case in artesian wells. The confining stratum beneath the porous bed demands less critical attention than that above, for if the layer next beneath the water-bed is defectively impervious, some lower layer will stop the water. It is only when the lower layers are so situated that they can carry the water out again to the surface, at a lower level than the water-bearing bed above, that they can discharge it, however leaky. This is not usually the case. As a rule, when beds are bent into a basin, or are inclined, the lower layers outcrop at higher elevations than those overlying them, as illustrated in Fig. 12. But this is not always so, and, even when so at first, unequal erosion

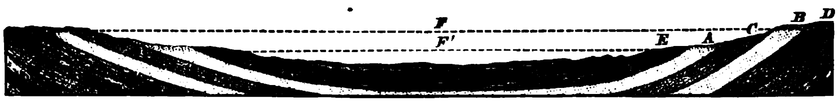

FIG. 12.—Section illustrating the usual order in which the strata of a basin come to the surface. A and B, porous beds; D and E, impervious beds; C, a half-impervious bed; F' and F the water levels of A and B, respectively.

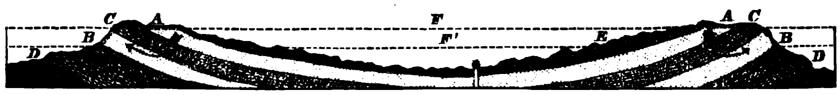

FIG. 13.—Section illustrating the possible effect of erosion upon strata originally like those in Fig. 6. A and B, porous beds; D and E, impervious beds; C, a half pervious bed; F and F' the water levels of A and B, respectively. If the stratum C is not practically a confining layer, the water from A will pass through it and escape at the edge of B, so that a flow cannot be obtained at a higher level than it, but may be had below the line F'.

of the surface may reverse the order of height of outcrop, as illustrated in Fig. 13. The consequence of a possible defect in the layers underlying a water-bed are illustrated in Figs. 13 and 14, and the descriptions appended to them. The confining strata below cannot, therefore, be neglected, though usually less imperative of critical attention than those above.

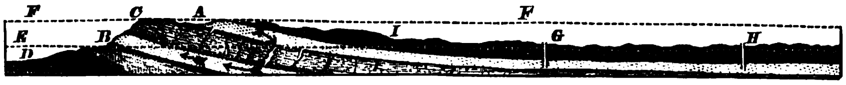

FIG. 14.—Section illustrating the failure of an artesian well, because of defects in a confining bed below. A and B, porous beds; D and I, impervious beds; C, a defective confining bed; E, the water level of the stratum B; G and H, wells that do not flow. The bed A might give a flow at G and H but for the defect in C, which permits the water to descend into B and escape through its outcrop, which lies below the surface of G and H.

2. *The confining stratum above.*—The character of the strata that overlie the water-bearing bed is critically important, for the water, being under pressure, tends to rise through them, and, if they are in any degree penetrable, it will, to that extent, escape, and relieve the pressure, and thus reduce or prevent the flow. When the capacity of the water-bearing bed is great, and the fountain-head high, moderate defects in the cover-bed merely cause a reduction in the volume and height of flow; but when the conditions are closely balanced, either because of low head, feeble supply, or obstructed passage, he who assumes to foretell results has need to make careful estimate of the amount of leakage through the covering strata.

*a.* It may be noted that the leakage will be reduced in proportion as the pressure is lessened, so that, in nearly-balanced cases, the loss is less—other things being equal—than in cases of high head and free passage, *but it is more critical in determining success or failure.*

*b.* The most essential consideration, the nature of the rock, has already been discussed. In a more summary and general way it may be here restated that the effective imperviousness is somewhat nearly measured by the total amount of clayey constituents. But this is rather a convenient generalization than a safe rule.

*c.* Efficiency increases with thickness. If the cover-beds are of the highest impervious character, there is little need that they should be very thick, unless the fountain-head is so high that increased weight is needed to counterbalance the hydrostatic pressure—an improbable case. But when the degree of imperviousness is inferior, the element of thickness is not without consequence, in itself, and, taken in connection with the following point, may be decisive.

*d.* The element to be recognized here is, I believe, essentially new to discussions of the subject,[4] viz, the height of the surface of the common ground-water in the region between the proposed well and the fountain-head. It is a familiar fact that the common underground water stands at varying heights. Our common wells testify to this. The subterranean water-surface is almost invariably higher than the adjacent streams, and slowly works its way into them by springs, seeps, and invisible percolation. Speaking generally, the underground water-surface rises and falls with the rise and fall of the land-surface, only less in amount. Now, if the subterranean water in the region between the proposed well and its source—which we may call the cover-area—stands as high as the fountain-head (except at the well, where, of course, it must be lower), *there will be no leakage*, not even if the strata be somewhat permeable, for the water in the confining beds presses down as much as the fountain-head causes that of the porous bed to press up, since both have the same height. Capillarity does not disturb the truth of this. Under these conditions a flow may sometimes be secured when it would be impossible if the intervening water-surface were lower.

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[4] I discussed this subject extemporaneously before the Wisconsin Academy of Science in December, 1880, but did not write it out for publication. The point is treated in Vol I, Geol. of Wis., p. 692.

If the water between the well and fountain head is actually higher than the latter, it will tend to penetrate the water-bearing stratum, so far as the overlying beds permit, and will, to that extent, increase the supply of water, seeking passage through the porous bed, and will, by reaction, tend to elevate the fountain-head, if the situation permit.

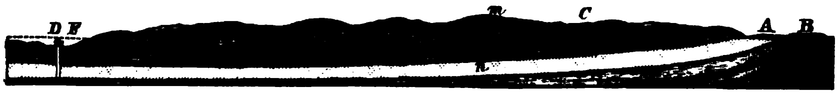

FIG. 15.—Section intended to illustrate the aid afforded by a high water-surface between the fountain-head and the well. A, a porous bed; B, a confining bed below; and C, a confining bed above. The dark line immediately below the surface represents the underground water-surface. Its pressure downward is represented by the arrow *m*. The pressure upward due to the elevation of the fountain-head is represented by the arrow *n*. The line F represents the level of the fountain-head. There can be no leakage upward through the bed C except near the well D. There may be some penetration from the bed C into A, which would aid the flow.

I conceive that one of the most favorable conditions for securing a fountain is found when thick semi-porous beds, constantly saturated with water to a greater height than the fountain-head, lie upon the porous stratum, and occupy the whole country between the well and its source, as illustrated by Figure 15. This is not only a good, but an advantageous, substitute for a strictly impervious confining bed. Under these hydrostatic conditions, limestone strata reposing on sandstone furnish an excellent combination.

If on the other hand the underground water-surface between the proposed well and the source of supply is much lower than the fountain-head there will be considerable leakage, unless the confining beds are very close-textured and free from fissures. For example, if it be 100 feet lower there will be a theoretical pressure of nearly three atmospheres, or about 45 pounds to the square inch upward, greater than that of the underground water downward, disregarding the influence of capillarity, and this will be competent to cause more or less penetration of the water upward through the pores and crevices of the rocks, and consequent loss of head and forcing power.

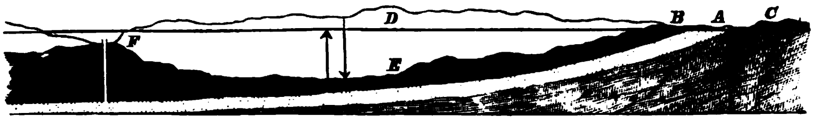

FIG. 16.—Double section illustrating the effects of high and low water-surface in the cover-area. (For explanation see text.)

Both of the above points may be illustrated by the accompanying double profile, in which A represents a porous stratum inclosed between the impervious beds B and C. The source of water-supply is at A, and the proposed well at F. Let E be supposed to represent the surface of the ground (and, for convenience, also, the surface of the common groundwater) in one of the two supposed cases, and D the surface in the other. The arrow springing from the surface E represents the upward tendency of the water in the porous bed, owing to pressure from the fountain-head, while the arrow depending from the line D represents the downward pressure of the ground-water whose surface is represented by D, and is, it will be observed, more than equivalent to the upward tendency due to pressure from the fountain-head. A flow at F could very safely be predicted if the surface were as represented by D, while it might be doubtful whether one could be secured if the surface were as represented by E.

My attention was first directed to this consideration by observing that where the intermediate country was elevated and had a high water-level, wells flowed at heights surprisingly near theoretical estimates, almost no deduction for obstruction and leakage being necessary, whereas in those cases where the opposite was true there was a very considerable falling short of theoretical estimates.

## THE INCLINATION OF THE BEDS.

The water-bearing bed and the confining strata that embrace it must be inclined so that the edge which comes to the surface shall be higher than the surface at the proposed well, else there can be no elevated source of supply for the flow. The ideal conditions are furnished when the strata sag in the center, while the edges are upturned so as to form a basin. The water then enters the rim of the porous stratum and fills it up to the level of surface drainage. If, now, this saturated stratum be tapped somewhere toward the center of the basin, at a point lower than the water-level in the rim, a stream will be forced to the surface. But it is not really necessary that the beds form a basin. If they are inclined so as to expose their edges on one side, and if by any means the porous bed is choked up in the other direction, so that the water cannot escape, a flow may be obtained without regard to what may be the position of the opposite edge. It is highly probable that our sandstone beds as they pass off from the old shore belt, along which they were formed, into what was then the deeper part of the ocean, gradually change from coarse, open sandstone to fine-grained rock, and so cease to be readily permeable to water. Along the South Atlantic border, for instance, there are sandstone beds that pitch down beneath the sea. But we have no need to search the coast of North Africa for the opposite edge, for there is no reason to doubt that the sandstones soon thin out under the ocean, and are replaced by a close-textured, deep-sea sediment. A similar fact is true of large basins generally. It is not necessary to consider the great interior basin defective because of the depressed lips through which the Mississippi and Mackenzie Rivers flow out of it. Experience teaches that we may safely neglect the opposite side of the basin in such cases and consider the problems presented as if the porous beds became impermeable somewhere in their downward extension.

But even if the sandstone formation is continuous and crops out at a lower point than the well, it is not necessarily impossible to secure a flow, though cases of this sort must be considered with much circumspection in attempts to prejudge success or failure. Another principle enters here and demands consideration. Let us recall the fact that sandstone strata are chiefly the product of wave action along shore belts and off-shore shallows. It stands to reason and observation that they are thickest and coarsest along the shore edge and thinner and finer in the off-shore portion. When these beds are afterwards lifted and become part of the continent, the former shore border is almost universally most elevated, and becomes the entrance edge for subterranean waters. (See Figures 12 and 17.)

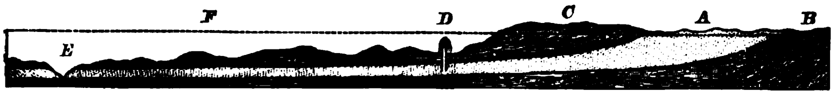

FIG. 17.—Section illustrating the possibility of a flow from a bed even when exposed at a lower level A, a sandstone bed, thick and coarse at the right, its shore edge, and thinner and finer at the left. B and C, confining impervious beds. F, the water level in A. D, a well which may flow notwithstanding the lower exposure at E.

Now, this edge has a greater water-conveying capacity than the off-shore portion, both because it is thicker and because it is coarser and more open. If, therefore, the surface supply is generous and the outcrop in the opposite direction is distant, even though it is lower, it may be an inadequate means of discharge, because of the great resistance encountered by the water in threading its way so long a distance through the minute pores of the close rock. Under these conditions a well-bore near the fountain-head (as at D, in Figure 17) may offer to the water a route of less resistance. The greater ascent through the well may be counterbalanced by the greater resistance of the long underground passage.

The element of resistance makes itself manifest even in cases where there is no reason to suspect a change either of thickness or of texture of rock. Several important wells at Oshkosh, Fond du Lac, Watertown, and Palmyra, Wis., flow from formations that outcrop, within 50 miles, at notably lower levels. These outcrops, however, are not in the line of slope from fountain-head to well, but more nearly along the line of strike at right angles to it. All these wells probably owe their success to the high subterranean water-level between the wells and their sources, as above explained, but resistance to flow through the water-bearing bed seems also to serve an important function, else the entire head would be relieved through the low outcrops.

It is, of course, to be borne in mind that resistance from friction is only developed when motion begins, and motion begins only when the water escapes, so that loss must always be reckoned when frictional resistance is assumed. The function of this resistance is only to render available a portion of the aqueous flow at a height greater than the lowest but inadequate outlet. The same principle is involved when several wells at different heights draw upon the same stratum.

*Height of outcropping beds.*—The relative height of the outcropping edge of the water-bearing stratum is a consideration of the first importance. It is obvious that this edge must be elevated, so that the water within it will stand high enough above the site of the proposed well to force an efficient flow after deduction is made for leakage and the obstruction encountered in the passage. How much higher than the well it must be is a complicated, practical problem, in which large deductions from theoretical estimates must often be made. It depends upon (1) the distance of the well from the source of supply; (2) the capabilities of the porous bed; (3) the character of the confining strata, and (4) the topography of the intervening land and the ground-water surface, as previously explained. These elements are so varying in their combination that it is impracticable to give any definite general rules applicable to wide areas. The best guide will be found in studying the results of experience in regions presenting conditions, as nearly as possible, similar to those of the proposed well. A study of the local and special conditions of any proposed well is essential to a trustworthy prophecy of results.

## THE RESERVOIR OR FOUNTAIN HEAD.

It is often convenient to speak of the source of supply as the reservoir. Erroneous impressions, however, are likely to arise from the use of the term. Two such are quite current, and need to be dismissed. The one is the assumption that the reservoir is a surface lake, the other that it is an underground pool, occupying a cavernous cistern, as it were. A surface lake is an extremely improbable source of an artesian flow. It has already been indicated that the water must have a *ready* *entrance* and flow through the porous stratum to give an efficient fountain. But most lakes owe their existence to the fact that they have impervious bottoms, otherwise the water would pass into the earth beneath. This fact stands in the way of their serving as sources of artesian wells. Far from being looked upon as special fountain-heads, lakes are to be regarded in precisely the opposite sense. They show that the rain-fall, instead of going into the strata to feed the fountain, is held at the surface and exposed to loss from evaporation and overflow.

The rain-fall of a region is discharged in three ways; (1) evaporation, (2) surface drainage, (3) underground percolation. Artesian wells can avail themselves only of the last. Whatever increases the first two decreases the last. In so far, therefore, as impervious surface basins aid evaporation and surface discharge they detract from the copiousness of the underground supply.

It is a compensating fact, however, that surface drainage is usually imperfect in lake regions, as the existence of the lakes themselves testifies. Possibly all, or more than the loss from evaporation, may be gained by this reduced surface flow. This, however, does not destroy the force of the general observation, that a lake is not to be regarded as the special reservoir of an artesian fountain.

The notion of a subterranean pool has little more to support it. Tubular channels and cavernous spaces undoubtedly exist, and are occasional sources of flow, or means of passage, and so are, in a sense, reservoirs, but not in the import of the term as used in connection with artificial fountains, *i. e.*, in the sense of a fountain-head.

The reservoir or fountain-head of most artesian wells is simply the water contained in the water-bearing stratum above the level of the point of flow, or, in other words, the water in the elevated margin of the water-filled stratum. To fashion a simple illustration, conceive a piece of lead tube to be inclined and filled with sand, the lower end being closed; let water be poured in until the sand is completely saturated. Now a miniature flowing well may be formed by drilling a small hole near the lower end. The water in the sand will run out, and, if renewed at the upper end, the flow will be continuous. This would be analogous to an artesian well, save that here there is a cylinder of water-filled sand, instead of a sheet. Now the reservoir in this case is the *water in the sand* in the upper part of the tube. In like manner, in artesian wells, the reservoir, so called, or the fountain-head, is the water contained in the elevated edge of the porous stratum.

This is supplied by the rain-fall, and we are thus led on, naturally, toward that ultimate source, but, on the way we will consider the means of gathering and delivering it to the water-carrying stratum.

### THE COLLECTING AREA.

The outcropping edge of the porous stratum is practically the gathering area. Its extent depends not only upon the thickness of the bed, but on the angle at which it comes to the surface and the effect of erosion upon it. If the porous bed is thin, and outcrops at a high angle, its edge will not occupy much space at the surface, and will consequently be incapable of gathering in a large supply from rain-fall. On the other hand, if the thickness is great, and if the stratum comes to the surface at a low angle, so that its beveled edge is wide, it will have considerable extension at the surface, and be competent to receive and transmit a large supply of water.

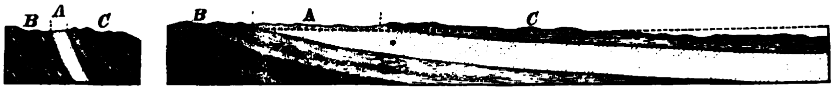

FIG. 18—Section showing the dependence of the collecting area on the thickness and slope of the porous beds. In the left-hand figure the porous bed A is thin, and, coming to the surface at a high angle, gives but a small section. In the right-hand figure the bed A is thick, and, coming to the surface at a low angle, its beveled edge is broad.

*Effect of erosion and surface configuration.*—Porous beds are usually more easily eroded than impervious ones, though this is by no means a universal rule. Soft clayey shale may be more erodable than even friable sandstone. The effect of greater erosion is usually a reduction of the surface area of the stratum, as illustrated in the accompanying figure.

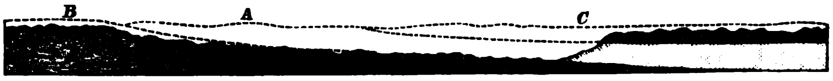

FIG. 19.—Illustrating a common effect of erosion upon the surface area of the porous stratum, and the contour of the resulting basin. The dotted lines show the original contours.

The adverse influence of this reduction is, in part, offset by the favorable contour of the depression so produced. A not uncommon form is a gently sloping plain, covered with a sandy absorbent soil, the natural result of the disintegration of the porous stratum, and these may render a nearly complete compensation.

The erosion of strata of unequal resistance usually results in very ragged, dissected edges. This may much increase the area tributary to the absorbent stratum, and be another source of compensation.

If the region of outcrop is much elevated, and the surface slopes are rapid, the rain-fall runs quickly away, and a less proportion of it is absorbed. In flatter regions, the surface discharge is less rapid and gives greater opportunities for subterranean percolation.

In considering questions relating to small wells, from which only a moderate discharge is demanded, it is sufficient to know, by the aid of ordinary wells sunk on the outcropping edge, what is the height of water and generosity of supply in the porous stratum; for, in regions of ordinary rain-fall, a very small surface will gather a sufficient amount. Even if the outcrop is very unfavorable, failure will not be likely to result from inadequacy of surface supply. But when very large delivery is demanded, these considerations are not to be entirely neglected. Without doubt, inadequate delivery at the well is more often due to other causes; but a superabundant volume of water, pressing for entrance and passage through the porous bed, is a condition much to be desired when important and expensive enterprises are to be undertaken.

### ADVANTAGES OF LOW INCLINATION OF THE STRATA.

In addition to presenting a larger collecting surface, there are two other advantages usually afforded by a low inclination of the strata:

1. If the productive bed dips but slightly, it lies within available reach beneath a larger area. If it dips rapidly, it soon attains a great depth, unless the surface slopes with corresponding rapidity.

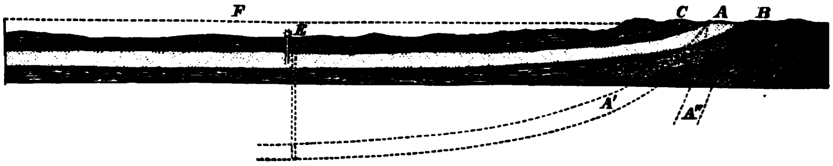

FIG. 20.—Section illustrating the advantages of low inclination. A, a porous bed; B and C, impervious beds. A' and A'' indicate porous beds of higher dip.

2. Another advantage is usually found in texture. The original position of sandstones and similar beds is essentially horizontal. If they are tilted, it is only because force has been brought to bear upon them. Some degree of compression and consolidation is the natural result of this action, increasing with its intensity. The porosity of highly disturbed beds is, therefore, liable to be inferior to that of those less disturbed, other things being equal.

So, also, the deeper the beds are buried the greater the weight of superincumbent strata, and the greater the tendency, probably, to the filling of the pores by depositions from infiltrating solutions.

The ideal stratigraphical conditions are found, therefore, when the beds have been gently lifted into an inclined position by a general crust movement, leaving them as little curved and depressed as is consistent with securing the proper head. A high and efficient flow depends more upon favorable conditions of underground passage than upon a high-rimmed, deeply-depressed basin. This is not altogether the popular impression, fostered by the unnecessarily distorted figures of current treatises.

### SURFACE CONDITION OF THE POROUS BED.

The facility with which water enters the porous stratum may be affected by the superficial mantle of soil and other unconsolidated material that conceals it. In those regions that are not overspread with Quaternary deposits of distant origin, the soil is mainly derived from the decomposition of the immediately underlying rock. In other words, the exposed margin of the bed has simply been disintegrated.

A porous rock usually gives origin to a still more absorbent soil, so that its decayed edge drinks in all the more readily the waters precipitated upon it. In the drift-bearing regions, the disintegrated surface was more or less rubbed away by glacial action, and then overspread by a sheet of mixed soil and rock-rubbish of the most varying character, sometimes absorbent, sometimes impervious, often presenting in its own alternating layers all the conditions (and sometimes the most fruitful ones) of artesian fountains. There is a certain disposition of the drift to partake of the nature of the stratum beneath, but this has important limitations. On the whole, the drift tends toward imperviousness, and has the effect of retaining the waters at the surface. Its superficial contour is usually irregular, having been formed under the compulsion of glacial action, and not in conformity to drainage demands, so that the water is discharged from the surface less promptly than in most other regions, and more time for penetration is permitted. This, in some measure, counteracts the effect of its imperviousness. But, in truth, the formation is so varying, in its embrace of glacial, fluviatile, lacustrine, and marine deposits, that all general statements are inadequate, and even in some measure misleading. Little more can be done here than to invite attention to the diverse influence of this most irregular surface mantle.

## RAINFALL.

For the ultimate source of these fountains we are led up manifestly to the clouds, and the chief question relates to the adequacy of the supply they pour out upon the collecting area. There lurks an ambiguity, however, under the term adequacy. To what adequate? To furnish all that we can use and waste, or all that the strata may drink? The amount that may be desired is diverse in the highest degree, embracing the moderate needs of the farmer for his kitchen and cattle, the larger service of the manufacturer for his different uses, the great consumption of cities for their baths, sewers, lawns, and streets, and the almost limitless demands of irrigation. If there were no limits to the available supply it would be difficult to set bounds to the drafts that would be made upon it. On the other hand, the amount which the strata can drink in, carry underground, and deliver through the well has much more definite limits; and this is clearly the better standard by which to judge the adequacy of the rain-fall, for when it has furnished to the strata all that they can take and deliver, it can do no more. It is adequate to the existing conditions, if not to our possible desires. Any failure to yield more is chargeable to the earth and not to the sky.

Still, in the absence of a full knowledge of the subterranean conditions, the possible competency of the rain-fall may be considered.

*Contrasted ratios of supply and demand.*—Very generous or very meager possibilities will result from computation, according to the region put under estimate and the want to be supplied. In the more humid districts the wants of the land are satisfied and the artificial demands are limited chiefly to domestic and sanitary uses. The supply is great and the demand small. In the more arid regions the land is thirsty also, and there is an enormous demand for irrigation. The supply is small and the demand great. So, unfortunately, the greatest demand and the least supply are mated.

The ratio of rain-fall to domestic needs is usually high. There falls upon every 50 feet square in average habitable regions more than the highest *per capita* allotment of cities, even under a Parisian régime. But the ratio of rain-fall to agricultural demands, though sometimes high, is often low. The precipitation upon the 50 feet square falls far short of furnishing food-support for an individual. The shadow of an ox covers half space enough to collect the water he drinks, but it would be a very partial supply for the sward he grazes.

While, therefore, in humid regions the rain-fall, considered apart from loss, is usually ample for the demands which there commonly arise, a little inspection shows that in arid regions it is quite inadequate for the demands which *there* arise.

### IRRIGATION BY ARTESIAN WELLS.

Artesian wells do not manufacture water. They do not even bring to the surface more than goes down from the surface. The total water supply of any given region is not, therefore, increased by them. They merely pour out at one point what has fallen and sunk elsewhere. If the total fall is inadequate to the agricultural wants of the total region, artesian wells cannot make it adequate. They may concentrate a sufficient supply upon a part but cannot supply the whole.

If the rain-fall of a district is but half what is necessary for agriculture, only half of it can be cultivated; but even to do this the entire quantity that falls upon one-half must be transferred to the other. This is quite impracticable, for if the agencies of both surface and underground streams were perfectly combined, there would still be the large loss from evaporation. The inadequacy of artesian wells under these conditions is apparent.

Artesian wells do not, and in the nature of the case cannot, collect their supplies from the whole face of the land, but only from the surface of the outcropping edge of the porous stratum. This usually occupies much less space than the country under which the stratum lies, and which would draw upon it for an irrigating supply. This holds true also of groups of porous beds that may underspread a given region. Now, when, bearing this disproportion of areas in mind, it is further considered that evaporation and surface drainage dispose of a large share of the rain-fall, and the wells must fail to deliver all that enters the strata, it is manifest that only very temperate hopes can be built on this as a resource in irrigation under conditions of high aridity.[5] We must not, however, overlook some compensating conditions.

1. *Equalization of supply.*—The porous stratum acts as an equalizing reservoir. The water runs in spasmodically, according to the varying rain-fall. It is delivered with much uniformity. The extra precipitation of wet months is thus distributed over the dry. In situations in which only a small supplementary amount in the dry months is needed this equalization may be made a serviceable feature.

2. *Supplemental reservoirs.*—As the water is needed for irrigation only during the productive months, while the flow is perennial, local reservoirs may be filled in the non-growing seasons, and used when needed. This does not essentially differ from the reservoir system as applied to surface streams, save that it has advantages in localization, security from floods, and ease of control. Both are limited by their expensiveness.

Quite a small rain-fall would suffice for crops if it were utilized to the best advantage. Deluging showers, seasonal floods, and winter rains are wasteful dispensers. If the rain-fall of the dry western regions could be distributed so as to be most serviceable, the unproductive tracts would be reduced to very narrow limits. In so far as artesian wells can be made to subserve this better distribution they are a valuable aid.

3. *Advantageous transfer.*—The porous beds beneath a dry tract may receive supplies from a more favored district. Often the upturned edges of the beds form the foot-hills of mountainous ranges, which are condensers, and receive a notably increased precipitation. Artesian streams, springing from beds thus favorably situated, become a means of transfer from more humid to more arid tracts, and, to that extent, tend to equalize the distribution in space, as they have before been shown to do in time. The draft upon the source has little prejudicial effect there, while it is a boon to the more arid district.

4. *Reutilization of the water.*—When water has once passed through the soil into the strata below, its agricultural usefulness is largely exhausted, until some agency again brings it to the surface. It is not entirely useless, for, by saturating the deep beds, it prevents succeeding rains from penetrating so far as they otherwise would, and, by thus arresting them nearer the surface, retains them in a more favorable position for utilization by capillarity and deep-root penetration. But such utility is limited, and at best small, compared to the advantage that

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[5] This has been well argued by Dr. C. A. White in "Artesian Wells on the Great Plains," North American Review, August, 1882; also Report of a Geological Commission appointed to examine a portion of the Great Plains east of the Rocky Mountains, and report upon the localities deemed most favorable for making experimental borings, Department of Agriculture, Washington, 1882, C. A. White, Samuel Aughey, and Horace Beach, commissioners.

might be gained by returning the water to the surface and redistributing it to the vegetation. It is clear that the greatest agricultural utility will be gained by continually bringing back to the soil the water that tries to run away, either on the surface or underground. In a perfect utilization there would be no streams, either above or below ground. The rain-fall would be absorbed by the soil, and thence by the plants, and by them returned to the atmosphere, the only loss being the inevitable evaporation from the moist soil. Of course, other valuable uses of water would thus be sacrificed to gain the highest agricultural utility. Now, artesian wells bring back to the surface water that had reached an unavailable depth, and permit it to be used a second time, to the advantage of both vegetation and the atmosphere, into which it is evaporated. There is in this an actual gain in utility, not a mere transference. There is, indeed, in some small measure, a greater total gain in using artesian than river water for irrigation, since the latter, in any case, aids by evaporation and lateral percolation, while the artesian stream is buried beyond use beneath impervious strata. These considerations urge as large a development of artesian wells in arid regions as practicable. While it is useless to think of them as a resource competent to restore productiveness to the total dry area, or even any great percentage of it, they form one of several means for its amelioration, which, when together brought into action, will react upon the climate in some measure, and, through it, feed their own sources. If the great volumes of water which the Colorado, Columbia, Missouri,[6] and other streams, above and below ground, bear away from the arid provinces could be led out upon the thirsty plains, absorbed, and given again to the atmosphere, very notable direct and indirect benefits would follow. To hope to accomplish the whole of this is doubtless utopian; certainly, to compass any great measure of it by artesian wells is chimerical, but it is none the less important to do all that is possible now, hoping, through the aid of its reactive results, to reach larger benefits in the growth of the future.[7]

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[6] Professor Powell has suggested that the utilization of the Missouri and other detritus-laden streams in irrigation would furnish at least a partial solution of the serious engineering problems they present.

[7] The State engineer of California reports, among other interesting facts, that 1,800 acres are irrigated by artesian wells in the counties of Los Angeles and San Bernardino. Nearly the maximum possibilities seem, however, to have been reached there, and although similar wells have been obtained in the great valley of California, we are not encouraged to think they will yield very great aid. (Rep. State Eng., Part IV, 1880. W. H. Hall, State Eng.; J. D. Schuyler, Asst. Eng.)

The Government commissioners above named give some of the results of attempts to secure artesian water on the great plains in the report previously cited.

Miss C. A. Salisbury, a teacher of Denver, informs me that a considerable number of successful wells have recently been sunk in that city, and that others are in progress. As yet no appreciable interference has been noticed.

Information from Hon. Horace Beach and others, as this is going to press, indicates that the number is approaching one hundred.

### ADEQUACY OF RAINFALL MEASURED BY CAPACITY OF STRATA.

Let us now return from the general limitations that relate to the competency of rain-fall, in its totality, to the more practical question of the relations of precipitation to the water-carrying capacity of strata. Any surplus beyond what can be drawn through the strata, however valuable otherwise, is no aid to the artesian yield. Let us seek a condition of equilibrium for our starting point. Let it be assumed that, under the collecting area, the water in the porous stratum stands at any given depth. If this is not high enough to give a flow at some favorable point in the distance, the case does not fall within our province, the rain-fall being wholly inadequate. Let the rain-fall be a little less meager, so that some head is gained. A well opened at the proper point will draw upon this supply in proportion to the facilities for subterranean passage. If these are free and open, a sufficient number of wells may entirely draw off the head and stop the flow from exhaustion. The remaining water will stand in equilibrium. Taking this as a base level, let us consider the effect of various stages of increase in the rain-fall. For a time every increase of the rain-fall will directly augment the flow. The ratio of increase of precipitation and flow will remain nearly equal until the facilities for traversing the strata begin to be taxed. If precipitation be increased beyond this, the first effect will be to raise the head. This will increase the force by which the water is pressed through the stratum, and augment the flow, but in a diminished ratio. Every further increase of rain-fall will add to the head, and likewise to the flow, until the water in the porous bed rises practically to the surface. Beyond that point, of course, an increase of the rain-fall has little effect, for the excess flows away on the surface or is lost by evaporation.

Now, when the strata of the collecting tract are shown to be full by such overflow, we are furnished with a direct indication, not only of a competency of rain-fall, but of, at least, some surplus. Herein is afforded a practical means of determining conditions, previous to actual trial by boring. The average height of the common water-level of the collecting area, as shown by wells, measures essentially the elevation of the fountain-head. If great fluctuations are produced in these by varying rain-fall, a corresponding effect will be felt by the proposed wells. But, if they are essentially constant, the element of precipitation may be assumed to be already high enough to lend its best aid; for stability is not likely to arise from any other cause than a surplus, regulated by an overflow. If this is not apparent, let a surface lake be taken as the representative of the underground one. Lakes which have no outflow are raised by rain-fall and lowered by evaporation and percolation, and of course fluctuate with dry and wet seasons. Those which are well fed and have an outlet, are nearly constant, for the obvious reason that the inflow will supply loss from evaporation and percolation in dry seasons, the overflow being slackened, while the overflow will draw off the surplus of wet seasons, being increased to meet the demand. The fluctuations are, therefore,confined to the few feet necessary to adjust the discharge to the surplus. So when the subterranean water-body has no outflow, except percolation and evaporation, through capillarity, it must grow with the increase of rain-fall and shrink with its decrease; but when fed to overflowing its surface is kept constant by the discharge of the surplus. Constancy in the level of a lake, amid changes of rain-fall, points clearly to an adequate supply and a regulating outflow. So constancy in the surface of the subterranean accumulation is a sign of a sufficient supply and an overflow of the surplus. In this case, to be constant, is to be full.

There is also a rude index of the surplus in the water, which, having been once absorbed into the upper edge of the porous bed, issues again in springs. If the porous bed were not already full, we must conclude that the water would descend into it and remain. It only comes forth because the stratum, being full, cannot admit it. Water may be shed from the surface while the earth below is still not saturated; but, having once entered a continuous porous bed it can only be assumed to re-issue because it cannot penetrate deeper.

These indications show the *existing conditions* of the supply, whether the stratum has been tapped or not, and serve as a guide for the next following enterprises. If, with additional wells, springs in the collecting tract dry up, and the water level sinks, without other assignable cause, there is reason to apprehend that the draft is being felt at the fountain-head in the consumption of the surplus, if not in the reduction of the reservoir.

Accepted with qualifications, the general judgment may be expressed that in regions which have sufficient precipitation for successful agriculture, the atmosphere pours upon the upper edge of the porous strata all that distant wells are able to draw through them. There will be some exceptions where enormous drafts are attempted under conditions exceptionally favorable for the exhaustion of the supply. But these are cases in which special study of all the conditions should be made before the enterprise is undertaken. There may be exceptions, also, when the carrying capacity of the porous bed is very great, while the collecting area is limited. But the general statement is fairly reliable in its application to the usual undertakings of citizens and corporations.

In that class of wells that are derived from the drift, or other local unconsolidated surface beds, more variation is experienced, and a closer relationship to the full measure of precipitation is observed. For in these (1) the beds of passage are usually open layers of sand and gravel, which permit a free flow of the water, (2) the reservoir is near at hand, so that the resistance between it and the well is small, and (3) the collecting area is usually limited. Under these conditions a large number of capacious bores may easily draw off all that the rain-fall can supply to the limited collecting area. Hence the amount of flow will fluctuate somewhat closely with the amount of rain-fall.

The cases in which an increase of rain-fall beyond a certain moderate amount will be most markedly felt are those in which the conveying capacity of the water-bearing bed is great, and the restraining power of the overlying beds imperfect. But if the water-bearing bed is close-textured and the cover-beds water-tight a moderate rain-fall will furnish to the collecting tract more than the stratum can deliver to any practicable number of distant wells, and will maintain the head near its maximum elevation.

From the foregoing considerations it appears that in a large class of wells of inferior stratigraphical conditions the amount of the rain-fall, beyond a certain moderate measure, is nearly, though not entirely, immaterial; whereas, in the class of more generous native capabilities, it is an element of supreme consequence.

## ESCAPE OF WATER AT LOWER LEVELS THAN THE WELL.

It is manifest that if the confining beds are pierced either naturally or artificially at a point lower than the surface of the well, the water may find relief from pressure by escaping there and fail to flow from the well. This is not often a source of failure from natural causes, where the overlying strata are thick, since the tendency in the deeper beds is rather toward the closing of openings and the healing of fissures than to the opening of a free passage way. However, in those regions in which profound fracture and displacement are common, failure from leakage through fissures is a source of apprehension.

The artificial defects consist mainly of wells previously sunk. It is a well-known fact that, where several are located near each other, those which are lower than the proposed well may already have consumed the full delivering capacity of the water-bed. The reverse may also happen. The new well, if lower than the previous ones, may draw off their flow. The remedy in these cases is simple. Either the flow of the lower wells may be reduced until the upper ones discharge, or else all may be brought to the same level by tubing. There is, perhaps, no better test of the delivering capacity of the water-bed than the degree of interference of neighboring fountains. In proportion as the supply is generous and freely delivered at the well, interference will be decreased. Notable interference of wells is a clear indication that some approach has already been made toward the limit of productiveness for that vicinity.

A hidden source of failure may be concealed in old deep wells, which either never were put under proper control, or which have fallen into neglect. The water may rise through these into loose superficial deposits or higher permeable strata and pass off horizontally, and thus afford relief of pressure without discovering itself at the surface. The remedy is either to block up these old wells deep within the confining bed, or else put them under the same control as the new one.

## CONDITIONS RELATING TO THE WELL ITSELF.

1. *The rate of delivery.*—It has already been made sufficiently evident that, however great the supply at the fountain-head, if the water must pass for a long distance through a thin sheet of close-grained rock, the rate of delivery at the well will be slow. If, on the other hand, the texture of the rock is open and the bed thick, the supply will be, other conditions favoring, very abundant.

A second condition of delivery relates to the well itself. It is clear that, if the bore merely touches the upper surface of the water-bearing bed, only a small space is afforded for the entrance of the stream. If, on the other hand, the well penetrates the formation deeply, the water can run in all along the sides, and, though the inflow at any one point may be moderate, the total amount from the large surface presented by the sides of the bore may be great.

*Methods of increasing the flow.*—*a. Torpedoes.*—Even where the entire thickness of the porous stratum has been penetrated, and all the advantages to be secured from increase of surface, in so doing, have been exhausted, the supply may still remain deficient. In some cases the yield is notably less than good reason gave encouragement to expect. The porosity of any bed is apt to be varying; and a well may be unfortunate in passing through a close-textured portion; or, if the water-bearing character is dependent on fissures and channels these may have been missed, though they may lie close at one side. In such instances an effective means of promoting a flow is found in the firing of explosives within the bore.[8] The manifest effect of an explosion is to fissure the beds extensively about the bore, and greatly facilitate the inflow. In the oil regions this device has been extensively used, and found both practicable and effective.

*b. Enlarging the bore.*—An obvious means of increasing delivery is an enlargement of the bore of the well. So far as this is intended to increase the surface within the porous bed, it is manifestly both inferior and more costly than torpedoing where the well is deep, but it has an obvious advantage in the larger conduit it affords for outflow. It is the practice of many drillers to first sink a well of the usual small dimensions, and then rim it out to the larger diameter desired. Besides the advantages in drilling this renders the cost of testing the chances at that point less. From the character of the flow obtained by the first operation it is possible to anticipate what will be the probable result of the enlargement. If the water issues with great force, it is manifest that the larger bore will greatly increase the delivery, because, in addition to the increased size, the friction is relatively less. If the flow be gentle, and the head known to be high, it is clear that the conveying stratum must interpose obstacles, and the indications are unfavorable to a very great increase from the enlarged well. If the fountain-head is low a full gentle flow is the natural sign of a generous stream, which might give an almost equally flush discharge from the enlarged bore.

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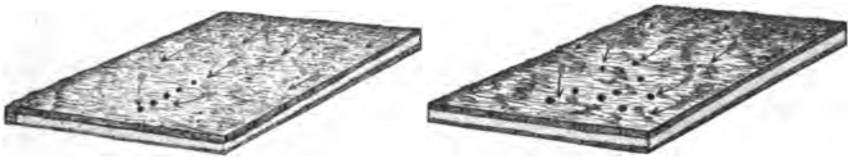
[8] Mr. John F. Carl, of the Pennsylvania Geological Survey, has given a very clear and detailed description of the construction and use of the torpedo chiefly employed in the oil regions. Second Geol. Surv. Penn. Oil Regions, III, 1880, p. 327.

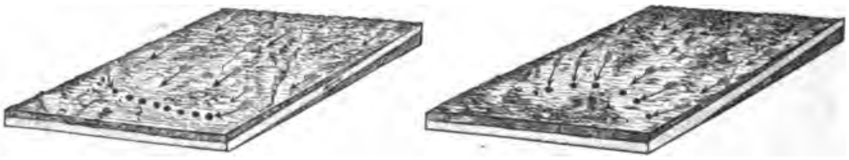
*c. One large or several small bores?*—In demands for large volumes of water, as in the supply of villages and cities, the alternative of one large or several smaller wells, is presented. On this question, the following suggestions may be offered. If the capacity of the water-bearing bed is known, or, from evidence, is confidently believed to be amply sufficient to pour into the base of the well all the water demanded from its mouth, so that the question becomes merely one of providing a suitably capacious delivery tube, it is manifest that, within the limits of economical drilling, the advantage lies with the single large well. But, in all cases where very large supplies are needed, and, especially, in all cases where the possibilities of the water-bed are liable to be taxed to their utmost, advantage may be derived by sinking several wells separated by intervals; for a much larger area of the productive stratum will thus be drawn upon. The vital issue, in this case, is not so much the providing of means for the water to rise to the surface, as the aiding of the water-carrying stratum in delivering it to the base of the wells. It is clear that the porous rock about the base of a single well, even though it be large, cannot furnish as great inflow as the rock about several wells, though they be individually, and even collectively, smaller. Besides, if torpedoes are used, the intake of each smaller well may be made approximately as great as that of the large one. The enormous wells that have sometimes been undertaken, are, therefore, not to be recommended.

*d. Distribution of wells.*—In the employment of several wells their distribution is a matter of some consequence. The normal direction of flow when it is once set up by virtue of the opening of an avenue of discharge is along a line drawn from the outcropping edge of the bed down its slope to the wells. Now, it is clear that if several wells are



FIGS. 21 AND 22.—Tabular sections of strata, showing disadvantageous arrangements of wells.

arranged along this line, the first one will be better placed than those which stand in its lee. These will be, indeed, measurably supplied by lateral flowage under the law of equal pressures, but less directly and freely. If the wells are disposed in a cluster, those on the exterior will partially cut off the supply of the interior wells. A more fortunate disposition than either of these would be an arrangement in a line at right angles to the direction of flow.



FIGS. 23 and 24.—Tabular sections of strata, showing advantageous arrangements of wells.

A still more advantageous arrangement, subject to local modification would be to dispose the wells in a curved line, convex toward the collecting tract, for when the draft of the wells has made itself felt upon the sheet of water flowing most directly from the collecting belt to them, the higher pressure, which the flanking portions still suffer, will cause a lateral inflow, and the curved disposal of the wells will be more favorable for receiving the ingathering currents than a rectilinear arrangement, being more nearly normal to the resultant pressure and flowage.

In respect to the degree of separation of the wells, it is obvious that so far as the mere question of the greatest reception is concerned the farther they are apart the better, for they will affect each other less; but, of course, practical considerations put a limit to their dispersion.

### LOSS OF FLOW IN THE WELL.

Having previously considered the favorable and unfavorable conditions that relate to the source and underground course of the flow, we were led, in the last paragraphs, to touch upon some considerations relating to the well itself. Let us now come more squarely upon the topic and search for causes of retardation in the well.

1. *Friction.*—We have already incidentally referred to the fact that an increase in the diameter of the well diminishes the relative amount of friction, and that, so far as this element alone is concerned, the advantage lies with the larger wells. The introduction of a small delivery tube at the top of the well obviously increases the friction and diminishes the flow. There is an illusive impression abroad that a reduction of the size of the delivery tube will increase the height to which the water will flow. This is altogether fallacious. It perhaps arises from the fact that a reduction in the mouth of a discharge pipe may be made to increase the force of the jet thrown out; but this jet never rises so high as the water would in an open tube carried upward, and the water will rise to the same height in a large tube as in a small one.

2. *Lateral leakage.*—In being forced up, the water will flow off sideways at its first opportunity. If, therefore, at any point in the upper portion of the well, it finds a crevice, or channel, or a porous bed, which is not occupied by water under as great pressure as itself, it will escape laterally, instead of forcing the column to the surface. It is necessary to prevent this lateral leakage. Sometimes the necessities of drilling lead to a satisfactory prevention. In sinking the well through the soil, sand, gravel, clay, or other loose material that may lie above the bed rock, it is customary to force down an iron tube, and sink it a few feet into the bed rock, by using a larger bit than that employed for the rest of the well. If a good joint is made here, and the rock below is tight, the lateral leakage may be thereby cut off, but this is not always available nor usually reliable. Besides, in many instances, the upper beds permit much waste, and recourse must be had to special methods for its control.

3. *Control of flow.*—It is clear, upon consideration, that perfect control may be obtained by putting down a tube to the densest portion of the upper confining bed, if, by some device, the space surrounding it may be closed up, so that no water can rise outside of the tube. Formerly, this was done by a very simple and ingenious device, known as the ***seed-bag.*** A long, stout, leather bag is made in the form of a cylinder, open at both ends, and just the size of the well-bore. This is slipped on the lower end of the pipe, and the bottom of the bag securely fastened about the tube by wrapping with marline. A thimble just above the tie will aid in preventing slipping. It is then filled with dried flax-seed, and the upper end likewise closed around the tube. When thus adjusted it is lowered into the well to the point determined upon, and supported there until the seeds swell by absorbing water. This enlarges the bag so as to fit the bore tightly and shut off all water from rising outside the pipe, and so all is compelled to ascend through the tube to the surface, or, at least, as high as the pressure is competent to force it.

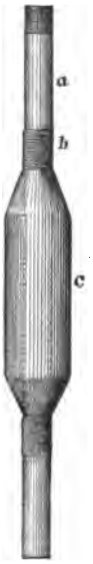


FIG. 25.—Seed-bag: *a*, delivery tube, leading to the surface of the well, and terminating below the seed-bag; *c*, a leather bag filled with dry flax-seed; *b*, marline wrappings to secure the end of the seed-bag.

A better and more convenient, but more expensive, packing takes advantage of the expansion of rubber disks when pressed together, instead of the swelling of flax-seed. A series of thick, washer-like rings of rubber are fitted about a section of pipe, so adjusted between iron disks that, after being put down, they can be screwed together, and so caused to expand laterally, and completely fill the bore.

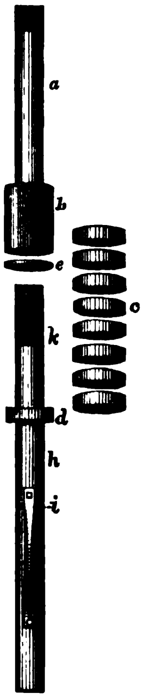


Fig. 26.

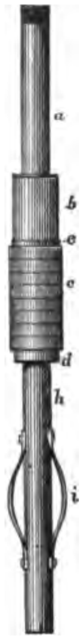


Fig. 27.

FIG. 26.—Rubber packing, shown apart; *a*, section of delivery tube, extending to the surface; *b*, a large thimble into which *k* screws; *e* an iron washer; *c*, a set of rubber disks, fitting on *k*, between *b* and *d*; *k*, a section of pipe on which is turned a long screw fitting in the thimble *b*; *d*, a disk forming the head of the screw *k*; *h*, a section of pipe extending about two feet below the packing; *i*, a spring to press against the walls and hold the pipe *h*, while the section *a* and thimble *b* are screwed upon *k*.

FIG. 27.—Rubber packing, shown screwed together as it is in the well.

The construction of the parts and their adjustment are sufficiently indicated in the accompanying figures, which illustrate one of the forms in use.

In a form employed in the oil regions, the expansion of the rubber disks, or single cylindrical one, is accomplished by pressing a conical hollow wedge between the pipe and the rings, thus forcing them out against the walls of the well.

In this case the packing is supported by a perforated tube, an "anchor," reaching to the bottom of the well. As the packing in artesian wells is often located near the top, the necessity for support from below excludes this form in most cases.[9]

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[9] This form is described and figured by Mr. Carl, Second Geol. Surv. Penn.. Rep. on Oil Regions, III, 1880, p. 322.

### HEIGHT OF FLOW.

1. *Measurement.*—When the flow has been confined to the tube by either of the above devices, it is an easy matter to determine the available height to which it may be carried. Where the pressure is moderate, this is easiest determined by adding pipe above the surface until the water no longer rises through it. But when the pressure is great, it would ascend to an inconvenient height, and a pressure-gauge of any available form may be substituted, and the height to which the water would rise, if suitably tubed, computed; each pound of pressure per square inch equaling 2.31 feet of rise.

2. *Prognostic estimate.*—The testing of the full strength of a generous fountain, already secured, is a comforting task, quite in contrast to the solicitude one suffers in attempting to estimate beforehand what height may be anticipated. Theoretically, the water will rise at the well to the same height as the fountain-head, and will flow at any elevation less than that. But the leakage of the confining strata and of the well reduce the height to which the water will rise, while the friction suffered in the long passage through the rock and the well will further lessen the altitude at which flow, of any notable vigor, will take place. Deduction must be made for all these elements. The special conditions which affect the estimate have been previously considered.[10] All the light that can be drawn from a careful scrutiny of these is demanded. The prudent expert will, however, seek assiduously a better and more truly scientific basis for his judgment. In almost every district wells have been attempted, and their results—whether successful or otherwise—if critically analyzed and interpreted, give valuable data, even though somewhat removed from the locality under consideration. The importance of recording and preserving the precise results of all enterprises, whether good or ill, cannot be too strongly urged upon drillers, geologists, and citizens alike, nor is it, perhaps, out of place here to urge that an intelligent respect be paid to the facts so developed; the respect, however, is no more important than the intelligence.

### DETECTION OF FLOW.

It has been remarked above that the water may rise from the bottom to some higher portion of the well, and there find escape by passing off laterally through the upper strata. In the absence of control, the water does not always rise and overflow. It is a matter of some practical moment, therefore, to know when a stream is struck which may yield a flow at the surface when put under proper control. (1.)

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[10] These conditions are so varied that I doubt the propriety of attempting any general statement of the deduction to be made from theoretical height. For Southern Wisconsin, I have found an allowance of about 1 foot for every mile between the collecting area and the site of the well to be as near a general estimate as I feel prepared to make; but even this is subject to considerable modification in special situations, and could not safely be adopted for other regions.

Such a stream usually discovers itself by a rise of water in the well, but this is not always the case. (2.) Some influence on the action of the drill is liable to be felt, which may arouse suspicion. (3.) In any instance of a strong flow, the drillings are apt to be carried away, so that when the sand-pump fails to bring these up, or brings only coarser material, there is good reason to believe that a stream has been struck, and the proper tests should be made. In enterprises that do not require a voluminous flow, tests should usually be made when such indications appear. It is ordinarily desirable to test the capacity of any stratum which gives any of these or other indications, before sinking to a lower one. It is advisable to make provision in the contract for such tests, since it is not always to the interest of the driller, once his machinery is set up and well at work, to stop at the more limited depth. The capabilities of the flow may be tested by the use of a tube and seed-bag, or by rubber packing, as explained above.

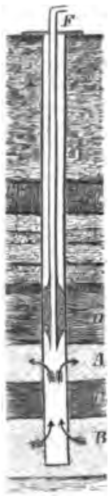

FIG. 28.—Section of a well, illustrating a negative test.

*Negative and false tests.*—1. It is possible, in perfect honesty, to make both a negative and a false test. Suppose that two porous beds, A and B (Fig. 28), separated by an impervious layer, are traversed, and the testing of the first has been neglected, either because it failed to give encouraging indications or for other reasons. It is now desired to test these. Suppose the seed-bag or rubber packing be placed above the upper one. Now, if both bear a water-level equally high, the test will be fairly made, and the result will indicate their combined capacity; or, if both heads are at least as high as the surface at the well, the test may be accepted. But suppose that the bed A has been cut into by erosion, or been reached by crevices, or is otherwise defective, while the other, B, remains intact and bears an elevated fountain-head. Under these conditions the water may flow from B through the bore into A, and escape laterally through it, as illustrated in the figure. Now, in this case the result may be either simply negative or positively false and misleading. If the lateral leakage through the stratum A effectually disposed of the flow from B, and there was no leakage in the upper portion of the well, the water in the test-tube would stand during the test at essentially the same height as before, and the result would be negative, merely failing to indicate a possibility that really existed. If, on the other hand, there was lateral leakage through the upper strata as well as through A, neither alone being quite competent to dispose of the flow from B, then the introduction of the test-pipe would cut off the upper leakage, leaving the bed A unable to dispose of the entire flow. In this case there would be a rise of water in the tube, and, possibly, a flow. The mischievousness of a test of this sort lies in the fact that it appears to be a true test, because it shows some result, while in reality it is false and misleading. The true test in this case can only be made by placing the packing between the porous beds A and B.

2. Take another instance where two porous beds, as A and B, figure 29, have been traversed. Let the packing be placed between these. Then (1), if A equals B in productive capacity, water will stand at the same height within and without the test-pipe *if there is no leakage in the upper beds.* (2) If the failure to flow was due to such leakage, then a flow will result from B, but the additional flow which might be secured from A is lost (see figure). (3) If A has a greater head than B, and if there is no loss above, the water in the test-pipe will actually be lower than that outside, as illustrated in figure 30. This may be said to be an ***inverted test***, and is less misleading than the false and negative tests, since it plainly indicates an error of manipulation. I have known such a case of reduced head as the result of an attempted test. (4) If, however, there is in this case considerable lateral waste in the upper strata, the valuable flow from A will be lost, just as before the test was made, while B may give a rise in the tube, or even a flow, which would foster the impression that a fair test had been made, while in reality the greater flow has been lost. (5) If A gives a feebler flow than B, but has an equal head, the test will fail of being completely satisfactory only in excluding the feebler flow from A. (6) If, however, A has a lower head, and is a possible means of escape for the flowage from B, then the packing has been placed at the right point, and the test gives the best results.

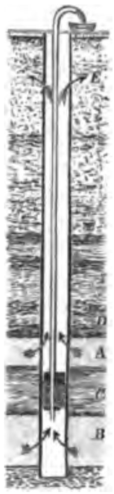

FIG. 29.—Section of a well showing a partial and misleading test.

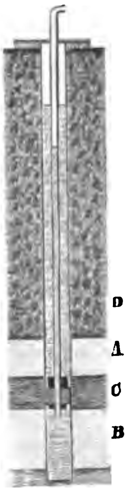

FIG. 30.—Section of a well illustrating an inverted test.

3. In still another case let A and B represent porous beds (figure 31), the lower of which is so conditioned as to drain the upper one by virtue of a lower outcrop, in the manner previously explained and illustrated in figures 13 and 14. (1) First, if the drainage-loss below is not complete, and if the packing is placed above A, as shown in figure 31, I, the result will be negative, if there is no leakage in the upper strata. (2) Should there be considerable loss there it will be cut off by the tube and packing, and some rise in the tube will be the result in most cases. In either instance the result is misleading, particularly in the last, because the small

rise of the water is apt to allay any suspicion as to the effectiveness of the test. The real fact, however, remains that the flow from the productive stratum is mainly lost below. (3) Suppose that the packing is located between A and B, as in figure 31, II, it will then shut off the flow from A, while that in B, because of a lower outlet, will fail to flow. Now, if there is opportunity for lateral leakage in the upper strata the water from A will rise in the well *outside* of the test-pipe and pass off into these open upper beds. (4) But if no such opportunity is afforded it may rise to the surface and overflow *outside* of the test-pipe, while the water within the test-pipe will probably be found to be lower than before the test was made. The proper method of testing wells known or suspected to present these conditions is to sink a simple bag of seed or other obstruction to a point in the impervious stratum between A and B, which, when it tightens in its place, will shut off the flow below. Then a tube with packing sunk to a point above A will effectually cut off all leakage in the upper strata, and the full capacity of the water-bed A will be tested.

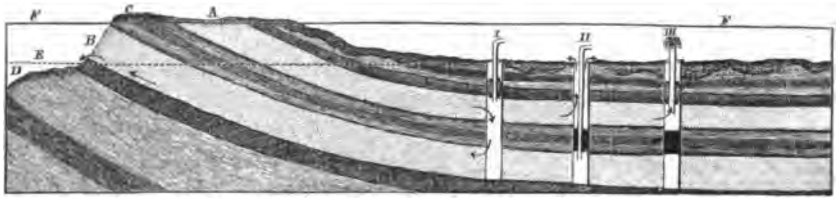

FIG. 31.—Section of strata and three wells, showing one correct and two erroneous tests. These wells are assumed to be independent of each other, and are placed together on the diagram merely for convenience.

These examples, while not exhaustive of possible cases, illustrate the nature of defective tests and the deceptive conclusions liable to be drawn from them. The remedy is manifest. Test each water-bearing stratum as it is encountered, or else vary the final tests so as effectually to exclude all liabilities to error.

### EFFECT OF TIME ON FLOW.

It is a common observation that the discharge of artesian wells declines in time, and the impression has somewhat obtained that this general fact is a necessary one. It is not unimportant, therefore, to consider the causes that lead to decline, since this is likely to be the best approach to the vital question, whether it is inevitable or preventable.

1. *Decline from loss of gaseous aid.*—We have thus far neglected a class of wells which flow, not from the pressure of an elevated fountainhead, but from the expansive force of pent-up gases, which are either disseminated throughout the water itself, like the carbonic acid in the soda fountain, or are contained in some hidden reservoir in communication with the water which is thus forced out. Wells of this class ejecting petroleum, gas, and water are familiar features of the oil regions.

A well whose flow arises from any such cause must decline as the gas relieves itself by escape, unless it is continually renewed by generation below, which is doubtless very rare. But while this class of wells lies without the province to which we are limiting ourselves here, it illustrates strikingly a cause of flow which has some little exemplification in the wells under consideration. Most waters that have stood pent up in the depths of the earth contain, absorbed within themselves, a greater or less amount of carbonic acid and other gases. When relief reaches these by the penetration of the well they expand and aid in lifting the column, both by their elasticity and levity, so that when first struck the water frequently flows with a sparkling vigor not permanently retained. Gradually the pent-up gas relieves itself and the flow correspondingly declines. The main effect of this, however, is doubtless brief, and so far as this element is concerned the flow settles down into an essentially stable current.

2. *Decline from loss of heat.*—An exceedingly slow, and almost infinitesimal decline may be assumed to result from a change of temperature. The water entering at the fountain-head has about the average temperature of the region. That issuing from deep artesian wells is warmer by several degrees. This relative warmth by lightening the column aids, in some little measure, the flow. The heat is derived from the deeper strata which the artesian current traverses, and manifestly they are continually losing what the stream is continually gaining, and a slow process of cooling the strata is going on. The temperature of the current must decline accordingly, and the aid derived from the warmth be correspondingly lost. This decline is probably much too slight and too slow to be of practical moment, though I am not aware what observation may teach on this subject, if, indeed, it has received attention.

3. *Decline from increase of leakage.*—Reference has previously been made to the disposition of the water as it rises in the well to find lateral escape through the upper strata. It is, of course, the intention of the well-sinker, in putting in his final delivery tube and packing, to cut this off by lowering the pipe to a point below which this does not take place. But, being expensive, it is not inserted deeper than thought strictly necessary. Now, many beds permit lateral leakage in a feeble degree, which are yet in the larger sense impervious, as, for example, many of our limestones. The lateral leakage which they permit may be at first imperceptible, but under the high pressure, minute streams thread their way through the tiny openings in the rock, and, little by little, by virtue of their wearing and solvent action, increase their channels until at length, through their united influence, they make themselves felt upon the greater stream. In many cases there are some hundreds of feet of limestone exposed to this action beneath the packing.

Again, since the packing occupies, at most, but two or three feet in the bore, the water, pressing from below, may thread its way around it through the capillary passages, and, at length, by enlarging these to more considerable dimensions, find partial relief in that way.

It is evident that both of these sources of leakage may be corrected by inserting the tube and packing to a lower point.

4. *Decline from closure of the bore.*—It is a well-known fact that some rock-beds, under great pressure from the strata above, "creep" toward artificial openings, such as the shafts and drifts of mines. So small a perforation as a well-bore, with its walls arched against an inward yielding, and filled with a column of water exerting from one-third to one-half as much pressure as the rock, does not invite this action. But some beds are soft and plastic, as the clays and clay-shales, while other are loose and mobile, as the sands and half coherent sandstones. Beds of these kinds, at considerable depths, where the pressure is severe, may yield, and tend to close the bore. Of course, the friction of the current is increased by the assumed stricture, and tends to cut it away, but perfectly pure water has little corrasive power. In the more stable formations it may be doubted whether this is often an occasion of decline. In the newer and less consolidated beds it is to be apprehended that it is. Closure of this kind could be tested by lowering an expanding gauge through the delivery tube; and it could, probably, in most cases, be successfully rimmed out with an expanding drill without removing the tubing.

Closure may also arise from an accumulation of sand and other fine matter brought into the bore by the inrushing current.

5. *Decline from defective piping.*—Obviously, growing defects in the tubing and packing would favor decline. Iron piping rusts rapidly, especially if there are corrosive ingredients in the water. If the decline sets in only after a few years, and rapidly increases, suspicion points in this direction.

6. *Decline from exhaustion.*—The too current notion that a subterranean pool, which has been struck by a well, supplies it for a time and then becomes exhausted, may be dismissed without much consideration, for no such pool will be apt, under existing hydrostatic laws, to leave its deep-seated repose and pour itself out upon the surface merely because an opening is provided. If forced by a distant head, that head may be drawn down, but the pool will remain as full as ever. I can conceive of nothing but the collapse of the inclosing walls that could force it to evacuate, and that would give a violence of ejection and suddenness of cessation corresponding to the rate of collapse, a phenomenon quite different from that commonly referred to the exhaustion of a subterranean pool. The exhaustion is not in the imagined pool under the well, but in the distant elevated edge of the water-bed. If there is but a limited accumulation there and it is not promptly renewed from the surface the well may gradually draw it off. In doing this, it is obvious that the head is, little by little, lowered, and hence has less and less forcing power. The flow, therefore, declines gradually. A decreas-

ing flow from this cause will fluctuate with the rainfall upon the distant collecting area, and will renew itself with returning wet seasons. A decline followed by a permanent refusal to flow points to some other cause. Decrease of flow due to overdraft on the supply, or exhaustion of the fountain-head, has a more adverse promise than those previously noted, since it is, in the main, irremediable.

7. *Detection of the cause of decline.*—From a consideration of the preceding causes of decline I venture the suggestion, without knowing from experience how far it may be practicable, that the precise way in which the decrease takes place may give a clew to the cause. The decline from exhaustion of stored gases should set in early and proceed rapidly for a time, and then more and more slowly as the exhaustion of the gas proceeds. That from heat may be neglected. That from enlargement of capillary pores would set in tardily and increase slowly, and at length probably produce a total stoppage. That from rusting of pipes, or decay of packing would not be felt at all at first, and would probably increase rapidly when once started, until an entire cessation ensued. That from closure of the bore would be slow in coming into action, if due to the "creeps" or filling, but if due to caving, it would be sudden and probably complete. That from exhaustion of the fountain-head would be gradual and decreasing, and its flow would be renewed with every fresh atmospheric supply.

## CHARACTER OF THE WATER.

1. *Temperature.*—It is a well-known fact that the temperature of the earth increases as its interior is penetrated at an average rate of 1 degree for every 50 or 60 feet, and that waters arising from the deeper strata partake of their elevated temperature. The water of the celebrated well at Grenelle, near Paris, has a temperature of 82°; that of Saint Louis, 73°.4; that of Louisville, 76°.5; that of Charleston, 87°. When the temperature is notably above 70° it may be rendered serviceable as a source of heat. The hospital of Grenelle is said to be heated by the famous well of that place. Below the temperature suitable for this purpose the warmth renders the water less immediately palatable, but facilitates its distribution through pipes in cold weather by preventing freezing.

2. *Chemical impregnations.*—The water which descends from the clouds is nearly free from mineral ingredients. As it penetrates the earth, it gradually becomes mineralized by dissolving the soluble constituents of the strata. The extent to which it thus impregnates itself is, among other things, dependent on (1) the character of the soil and rock through which it percolates, (2) the depth which it penetrates, and (3) the time it remains confined within the earth. It

is not strange, therefore, that waters rising from great depths should frequently be mineralized in a notable degree. The saline combinations may be various, but the constituents are but the soluble ingredients of the strata. When these constituents are such as to impart to the water undoubted hygienic and remedial properties, there may be no occasion to regard this impregnation as unfortunate. But when considered with reference to common domestic purposes, the mineralization of artesian water is a condition of debatable value. For drinking purposes, a moderate mineralization is, on the whole, probably beneficial, rather than injurious, though authorities are not entirely agreed upon this point. For laundry uses, the property of hardness, usually communicated by lime and other salts, is objectionable and the incrustations deposited upon boilers detract from its serviceableness to manufacturers. It is usually, though not universally, harder than the river and lake water of the region. In all cases, where city supplies are contemplated, opposing preferences are apt to arise, when the choice lies between artesian water on the one hand, and lake or river water on the other. Those to whom purity is a supreme consideration, whether it be freedom from infectious germs, deleterious organic solutions, or mechanically-suspended sediment, lean strongly to an artesian supply. With those who, neglectful of these considerations, are more influenced by industrial utility, a surface supply usually commands preference.

To the general rule, that artesian waters are more impregnated with mineral salts than surface waters, exceptions are found in those cases in which the rain-fall directly penetrates sandy soil, and thence passes on at once into an open stratum of quartzose sandstone, from which, without penetrating deeply, or remaining long within the earth, or coming in contact with calcareous beds, it is brought again to the surface. Such waters are often notably soft and relatively free from mineral impregnations.

There seems to be sufficient evidence to justify the statement—in itself very rational—that the water of an inclined stratum increases in mineralization with its depth and distance from the outcropping edge. At the upper margin, it is only rain-water, filtered through the soil, which has already been subjected to much leaching, which is, indeed, often little more than the insoluble residue of disintegrated rock. As it penetrates farther, it increases the earth-material with which it has come in contact, and is commingled with waters that have slowly percolated through the capillary pores of the adjacent strata, which, being relatively impervious, are as yet but partially leached of their oceanic salts, much less their rock substance. Manifestly, the farther it penetrates, and the longer it remains imbedded in the deep strata, the more mineral matter it has opportunity to dissolve from them.

Now, on the first opening of an artesian well the waters rising from the depths are possibly such as have long remained within the strata from want of any other means of exit than the slow methods of diffusion and capillary penetration. But, on the opening of a generous outlet, these pour forth upon the surface, and those that flow down from the fountain head to take their places pass less slowly through the stratum, and, presumably, are less impregnated with mineral ingredients. In the lapse of time the track of the current must become relatively more leached of its soluble constituents than portions impregnated with more nearly stagnant water. Hence the progressive tendency of artesian water is toward less mineralization. Whether the amount of this reduction is of practical consequence, has not, so far as I am aware, been satisfactorily determined by careful observation, but the impression that the water becomes gradually purer from extraneous matter is a not uncommon one.

## LIMITS IN DEPTH.

The vitality of a false notion is often surprising. It is sometimes crushing to our faith in the survival of the fittest. A striking illustration is found in the wide-spread popular delusion that an abundant flow may always be found "if you only go deep enough." When we consider that rain-fall is the great source of the waters of the land, and that the strata, as a rule, become more compact as depth increases, it is apparent that a very nearly opposite presumption should displace this fallacy. It doubtless arises from the fact that the immediate surface beds are more or less dry, and that it is necessary to penetrate some small distance to reach the subterranean water-bed. It is not realized that when this is once fairly reached the most richly supplied aqueous horizon is found. The beds below grow closer in general, and present less opportunity for accumulation. If, in imagination, the relatively dry surface were removed the rest of the earth might be conceived as most copiously filled with water in the more open upper portion, and less and less permeated below, because less and less open to receive water. This is, of course, only a general law, subject to much modification, according to the kinds of rock which overlie each other in succession.

In view of this general presumption, it is folly to sink deep wells without some definite knowledge that a rock of porous nature lies below and presents the requisite conditions for supplying a fountain. The occasional luck of ignorance may find a flow, but it is not soothing to our pride of popular intelligence to note how thickly our land is punctured by needless follies, largely encouraged by the above fallacious conception.

Preliminary to sinking a well, as complete knowledge of the underlying strata as it is possible to obtain from the usual methods of geological inquiry should be gathered, and the depth of the well limited to that necessary to reach the most productive stratum. To be sure, there are regions in which, in the absence of specific knowledge, or when such as can be obtained is indecisive, the sinking of a deep well to test the strata is warranted by the importance of a favorable result; but the uncertainties of the issue and the financial hazard of the undertaking should be frankly faced. It is not to be inferred from these conservative remarks that failures do not result from the opposite cause, that wells do not often come short of success by stopping short of the proper horizon. The existence of such failures only adds to the importance of specific knowledge in lieu of broad proverbs and loose maxims.

The succession of strata is so various in different regions that general rules are few. There is one, however, of wide application whose observance would save the useless expenditure of large sums. The Archæan rocks, as before observed, are exceedingly unpromising of success in themselves, and do not overlie productive beds. Whenever, therefore, in the progress of drilling these are struck, work should cease, unless there are specific local facts warranting a deviation from the rule. A provision to this effect should be inserted in all contracts, since it is in the interest of both parties, for the drilling is usually very difficult and unremunerative at any ordinary rate per foot, while, there being no rational prospect of good results to the owner, the amount he pays, however unremunerative to the driller, is a dead loss to himself. It is not sufficient to insert the term *granite* instead of *Archæan rock*, as is sometimes done, since quartzites and other crystalline rocks, not fairly embraced under the term granite, even in its more extended sense, are included in the Archæan series, the penetration of which would prove alike unprofitable to driller and owner.

Locally there are other formations at which drilling should cease, either because no productive beds occur below, or because they are known to lie at unavailable depths. Specific knowledge of such local conditions is requisite for guidance in these instances.

## THE ART OF SINKING WELLS.

It does not fall within the proposed scope of this article to enter upon a detailed discussion of the art of sinking wells, of the difficulties encountered, and of the ingenious devices by which they are overcome, but a few general statements may not be without interest in themselves, while they lead the way to other topics whose discussion is more imperative.

1. *Superiority of methods in the oil regions.*—Were it within our province to discuss the art of drilling, it would be necessary to go beyond the field of artesian wells proper to find its highest development; for whatever may have been the result in other respects of the traditional strife between water and oil, that never agree, the latter has

proved itself the master as an incentive to the development of ingenuity and skill in the art of drilling. The innumerable practical difficulties that rendered the earlier attempts tedious and hazardous at the best, failures often, have been largely mastered, and the sinking of wells one or two thousand feet deep is now a daily successful occurrence. To the oil regions, therefore, we must turn for the finest examples of technical skill in this art. For an exposition of this development, detailed with much particularity, and accurately illustrated, I can refer to nothing better than the report of John F. Carl, on the Oil Regions of Pennsylvania.[11]

The methods of sinking artesian wells in common use, are either slight variations from those current in oil regions, or represent some of the earlier methods in leading up to the present stage, and which remain serviceable for the less exacting demands of the shallower wells. All are modifications of the ancient chisel drill, which, by being lifted and let fall, cuts its way into the rock, being at the same time rotated to keep the hole round, uniform, and vertical.

2. *Use of the diamond drill.*—To a limited extent, the diamond drill has been employed. It is essentially an iron tube, armed at its lower extremity with cutting diamonds so placed that when rotated the tube cuts its way into the rock, leaving a cylindrical core in the center. A current of water, forced down the interior of the tube, and rising outside, carries away the drillings. It is in great favor with geologists and explorers, because the core gives a complete, unmutilated section of the rocks penetrated.

3. *Driven wells.*—In sinking wells in drift, or other unconsolidated beds, simpler and cheaper devices are much in use. The most expeditious, when practicable, is the "drive well"; merely a tube, armed with a conical point, and a section of perforated pipe, forced into the ground by a maul, or by dropping a block or beam upon it, pile-driver fashion, until the perforated section reaches the porous stratum, when the water flows in and rises to the surface. This, of course, is limited to shallow wells, whose confining stratum offers no serious impediment to penetration. The bowlders of drift-beds sometimes impose obstacles, but in so simple an operation it is easy to withdraw the tube and try again.

4. *Earth augers.*—In other instances earth augers are used, not unlike the common post auger, by means of which a bore of large size is rapidly and cheaply sunk. This is, of course, subject to like interference in stony clays or very coarse gravel.

5. *Cost of wells.*—The expense of sinking a well manifestly varies greatly with the character of the strata, the depth, and the cost of power and labor in the region in which it is sunk. So far as my knowledge extends it is not customary to vary the rate for the different kinds of sedimentary rocks, limestones, sandstones, and shales. Where re-

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[11] Second Geol. Surv. Penn. Oil Regions, III.

quired to penetrate granite or other crystalline rocks, an increased rate is very properly demanded. To attempt to distinguish between limestone, sandstone, and shales would lead to endless difficulty, as they not only graduate into each other, but are often intimately interleaved. The driller, familiar with the general character of the strata of the region, demands an average price, dependent on depth. While this varies, an approximate idea of the expense may be obtained by reckoning from $2 to $3 dollars per foot for the first 1,000 feet, and an increase of a half dollar per foot for each 500 feet below that down to the limits practicable for drilling. To this is to be added the cost of tubing, which will vary greatly with the situation and character of the strata.

## RECORD OF DRILLINGS.

The importance of keeping a careful record of the strata encountered in the progress of drilling needs emphasis, both on account of its practical and scientific value. The record should embrace not only accurate measurements of the successive strata traversed, accompanied by careful notes on their character and a full suite of samples, but also a record of all features relating to their water-bearing nature. Some of these, that seem trivial, often have much significance when critically examined and expertly interpreted. If the diamond drill is used, the cores, of course, furnish an exceptionally excellent record in themselves, if completely and carefully preserved and placed in their natural succession, besides being an interesting exhibit of much geological interest. Since, however, these are apt to be disarranged, they should be consecutively numbered, as taken out, and, since the softer portions of the core are liable to be much broken, supplementary measurements and notes are also desirable.

From what has been previously said, the importance of knowing precisely where to locate the permanent packing is apparent. Economy dictates that it be placed as near the surface as prudent, not only to save the cost of pipe, but also the reduction in the size of the bore caused by the insertion of the pipe, and the consequent increase of friction. At the same time it is important to cut off all dangerous lateral leakage, and forestall an early decline in the flow of the well. An accurate knowledge of the strata penetrated is the only trustworthy means of doing this.

Again, when any defect in the first tubing and packing develops itself, a careful record is a valuable aid in detecting the nature and cause of the defect, and determining the means for its correction. The original driller may have thought his general observation and memory a sufficient guide for the first adjustment, but if years have passed, neither the driller nor his memory may be within available reach. The party contracting for the sinking of a well should invariably insist upon an accurate written record, which should be preserved and transmitted with the property. The authorities of civic corporations superintending public wells should place such records on file among official documents.

When resort is had to the use of torpedoes, the precise point at which they are to be located is a matter of vital importance, and the exact depth at which the effects of explosion will presumably produce the greatest effect can only be determined by an accurate knowledge of the succession of the strata and their varying characters.

Recurring to the discussion of the testing and control of waters derived from different beds, the need of specific knowledge becomes self-evident.

It is unnecessary to enlarge upon the scientific value of such records, not only as guides in the antecedent study of proposed wells, but as direct and positive knowledge concerning the geological column, and many subsidiary phenomena.

In summation, the aid rendered in determining temporary tests, the location of permanent packing, the detection of the cause and place of defects leading to decline, the relocation of any necessary repacking, the firing of explosives, either at first or subsequently, the predetermination of success or failure in other attempts, and the light thrown on various geologic questions, combine to emphasize the importance of careful records of the drilling and the preservation of its products.

*Interpretation of the drillings.*—To the inexperienced the interpretation of the drillings offers some puzzles and pitfalls, though the phenomena are in reality quite simple. When the prudent driller has procured the insertion of a clause in the contract releasing him from his obligation when "granite," or the Archæan rocks, have been reached, a question for the arbitration of the geologist is apt to arise, since the other contracting party, failing of success thus far, not unnaturally desires to drive deeper. Now, the question would not usually be difficult or misleading were the drillings which are submitted merely those of the rock at the bottom of the well. But the rods or ropes and tools of the drill, by their vibration, strike the walls of the well and rattle down grains or fragments from the strata above, and these, mingling with the true drillings, often produce a curious intermixture, and if the simple fact of such a double origin is neglected, a wild interpretation will be the inevitable result. The harder the bottom rock, and the more friable the rock above, the greater the disproportion between the true and the false drillings, especially when rods are used instead of rope. When working in granite, beneath Potsdam sandstone, I have sometimes found less than 10 per cent. of the samples brought up by the sand-pump to be bottom drillings. In these cases rods instead of ropes were used. The basis for discrimination between the true and the false drillings is found in the angular forms and the fresh fractures, interpreted in the light of previous knowledge of the strata, the rate of the drilling, the character of the stroke, and other attendant evidences. Only the direct stroke of the drill is usually competent to give chips of hard rock of any notable size having the fracture-forms peculiar to such an origin; and these are to be sought as the best indications of the constitution of the rock being wrought upon.

In the penetration of hard rock, steel flakes and splinters broken from the drill, and metallic films rubbed from it, are not uncommon features. Brought up wet, they soon rust and are liable to be interpreted as ferruginous ingredients of the rock. The inconsistency of their color with the magnetic susceptibility which the unoxidized core retains betrays their true character.

## AREAS OF FAVORABLE, DOUBTFUL, AND ADVERSE PROBABILITIES.

It is the proper function of geological investigation to ascertain the stratigraphic conditions which determine success or failure. As the outcome of completed investigations, it is possible to map off the face of the country into (1) areas in which success may reasonably be anticipated, (2) areas in which the conditions are nearly balanced, and in which local and indeterminate conditions will decide success or failure, and (3) areas in which the conditions are adverse, if not altogether prohibitory. The service which such maps are competent to render in encouraging the utilization of an important resource, or in teaching caution and circumspection where uncertain results alone can be anticipated, or in forbidding useless expenditure, need not be argued. Such classification of areas has been attempted in one or more states,[12] but a general map for our vast domain is yet a hope of the future.

From the foregoing considerations it is manifest that the areas of probable success must be the relatively low tracts, that the areas of adverse probabilities are the relatively high regions, and that the doubtful belts lie between. The fallacy of an abundant supply, " if you only go deep enough," is altogether overshadowed by the singular notion, not altogether uncommon, that high lands are favorable locations for artesian fountains. The origin of this surprising illusion I am unable to fathom.

The greatest sources of indefensible expenditure are (1) the selection of a location of too great relative altitude, in defiance of the simple fundamental principle of artesian flowage, and (2) the penetration of unproductive strata, after all favorable chances have been exhausted, in disregard of the fundamental laws that govern the distribution of subterranean waters.

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[12] Geol. Wis., Vol. I, p. 697.

*Special study.*—In the face of so many possibilities of failure, the importance of a special-consideration of the assemblage of conditions that surround a proposed undertaking, in a region not previously proved, or in a situation in any important respect dissimilar from those already tested, need not be pressed. The central purpose of this paper has been to call into prominence the varied qualifying conditions that solicit consideration, and, if possible, stimulate and aid those special discriminative studies which lead to an intelligent confidence of success or a prudent withholding from failure.

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